

STRIPES AND CHARGE TRANSPORT PROPERTIES OF HIGH- T_C CUPRATES

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Unusual features in the in-plane charge transport in lightly hole-doped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ single crystals are described. Notably, both the in-plane resistivity and the Hall coefficient show a metallic behavior at moderate temperatures even in the long-range-ordered antiferromagnetic phase, which obviously violates the Mott-Ioffe-Regel criterion for the metallic transport and can hardly be understood without employing the role of charge stripes. Moreover, the mobility of holes in this “metallic” antiferromagnetic state is found to be virtually the same as that in optimally-doped crystals, which strongly suggests that the stripes govern the charge transport in a surprisingly wide doping range up to optimum doping.

1. Introduction

In high- T_c cuprates such as $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO), the antiferromagnetic (AF) state gives way to high- T_c superconductivity when a sufficient number of holes are doped into the CuO_2 planes. The AF state of cuprates is therefore a natural starting point to establish the picture of high- T_c superconductors, but nevertheless their transport properties have not drawn sufficient attention. It has been generally believed that the hole motion inevitably frustrates the antiferromagnetic bonds and thus the doped holes must be strongly localized until the long-range AF order is destroyed. Indeed, the variable-range-hopping conductivity has been mostly observed in the AF state of cuprates,^{1,2} which is naturally expected for the localized holes. As a result, researchers have been discouraged by the apparent simplicity of this so-called “antiferromagnetic insulator” regime.

However, recent measurements in clean, lightly-doped $\text{YBa}_2\text{Cu}_3\text{O}_y$ (YBCO) crystals have demonstrated^{3,4} that the charge transport in the AF state is full of surprise: the temperature dependence of the in-plane resistivity ρ_{ab} remains to be metallic (ρ_{ab} decreases with decreasing temperature) across the Néel temperature T_N , anomalous features in the magnetoresistance imply that holes form stripes instead of being homogeneously

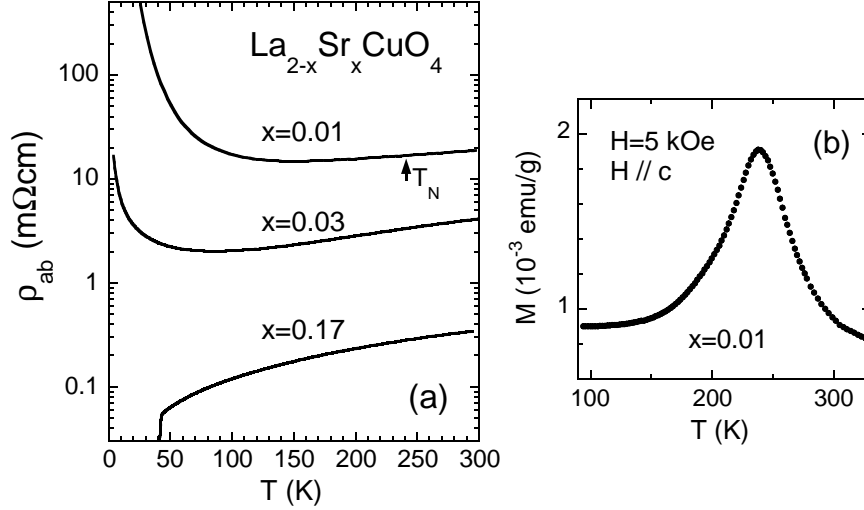


Figure 1. (a) Temperature dependences of ρ_{ab} of lightly-doped ($x = 0.01$ and 0.03) and optimally-doped ($x = 0.17$) $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ single crystals. (b) Magnetization of a large $\text{La}_{1.99}\text{Sr}_{0.01}\text{CuO}_4$ single crystal from which the samples for ρ_{ab} measurements were cut; the peak in $M(T)$ corresponds to the Néel temperature.

distributed, and along the c -axis the charge confinement characteristics are significantly affected by the Néel ordering. Motivated by these results^{3,4} on YBCO that we obtained in 1999, we have revisited the charge transport in clean single crystals of LSCO, where studying the lightly-doped regime is much more straightforward than in other cuprates; the hole doping p in the CuO_2 planes is equal to x , the Sr content, and T_N can be readily determined by susceptibility measurements.⁵

Here we show that, contrary to the common belief, the doped holes in clean single-crystalline cuprates are surprisingly mobile in a wide range of temperatures even in the long-range-ordered AF phase. This is possible when the electron system self-organizes into hole-rich stripes and hole-poor AF regions to facilitate the motion of charges. We further show that the hole mobility at moderate temperatures remains virtually unchanged throughout a wide doping range from the lightly-doped AF regime (hole doping of 1%) to the optimally-doped regime (hole doping of 17%) where the superconducting transition temperature is maximal. This strongly suggests that the hole motion is governed by the stripes all the way up to optimum doping, and thus the high-temperature superconductivity appears to be a property associated with the stripes.

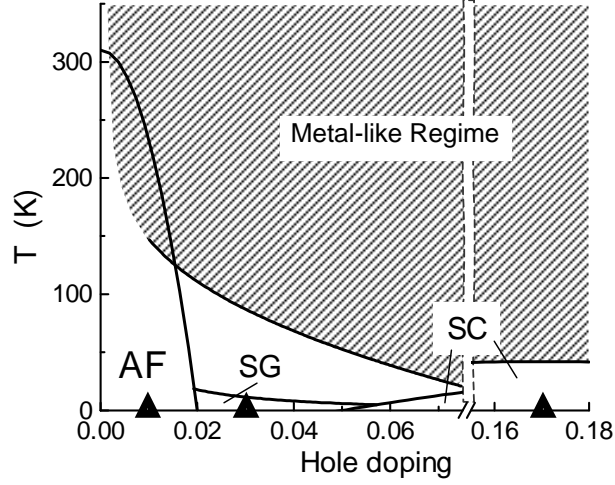


Figure 2. The antiferromagnetic (AF), spin-glass (SG) and superconducting (SC) regions on the phase diagram of LSCO; representative doping levels chosen for this article are indicated by triangles. The hatched region illustrates where ρ_{ab} shows the metal-like behavior ($d\rho_{ab}/dT > 0$).

2. Experimental

The clean single crystals of LSCO are grown by the traveling-solvent floating-zone (TSFZ) technique⁶ and are carefully annealed to remove excess oxygen, which ensures that the hole doping is exactly equal to x . The in-plane resistivity ρ_{ab} and the Hall coefficient R_H are measured using a standard ac six-probe method. The Hall effect measurements are done by sweeping the magnetic field to ± 14 T at fixed temperatures stabilized within ~ 1 mK accuracy.³ The Hall coefficients are always determined by fitting the H -linear Hall voltage in the range of ± 14 T, which is obtained after subtracting the magnetic-field-symmetrical magnetoresistance component caused by small misalignment of the voltage contacts.

3. Results

Figure 1(a) shows the temperature dependences of ρ_{ab} for LSCO crystals which represent three doping regimes^{1,7} on the phase diagram (Fig. 2): antiferromagnetic [the sample with $x = 0.01$ has $T_N \simeq 240$ K according to the magnetization data shown in Fig. 1(b)], spin glass ($x = 0.03$), and optimally-doped superconductor ($x = 0.17$). (More complete data sets can be found in our recent papers.^{6,8}) One may notice that, while the magnitude of the resistivity significantly increases with decreasing doping, the

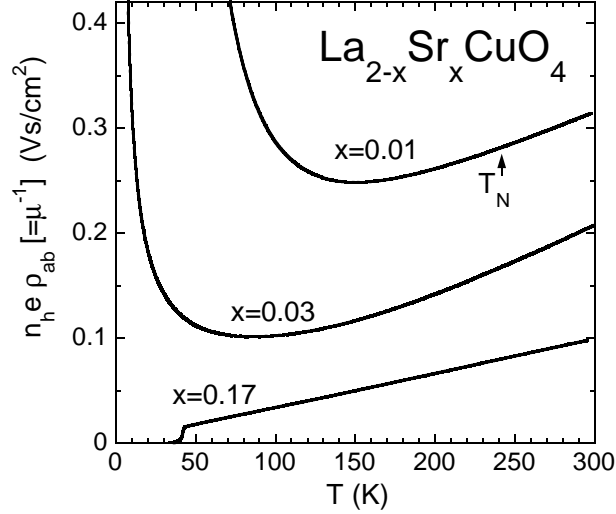


Figure 3. Temperature dependences of the normalized resistivity $n_h e \rho_{ab}$ of LSCO crystals, where $n_h = 2x/V$ is the nominal hole density. Note that $n_h e \rho_{ab}$ is essentially an inverse mobility μ^{-1} of doped holes.

temperature dependence at $T > 150$ K does not change much; in particular, in the sample with $x = 0.01$, ρ_{ab} keeps its metallic behavior well below T_N . This observation in the lightly-doped LSCO crystal clearly invalidates the long-standing notion that the metal-like behavior of $\rho_{ab}(T)$ in cuprates may appear only as soon as the long-range AF order is destroyed.

To examine whether the hole mobility actually depends on the magnetic state as crucially as has been expected, in Fig. 3 we normalize ρ_{ab} by the nominal hole concentration n_h , which is given by $2x/V$ [unit cell V ($\simeq 3.8 \times 3.8 \times 13.2 \text{ \AA}^3$) contains two CuO_2 planes]. The product $n_h e \rho_{ab}$ would mean just inverse hole mobility μ^{-1} if we assume the number of mobile holes to be always given by x . Apparently, the slope and magnitude of $n_h e \rho_{ab}$ at moderate temperatures are very similar, suggesting that the transport is governed by essentially the same mechanism for all three doping regimes; in particular, the magnitudes of the hole mobility at room temperature differ by only a factor of three between $x = 0.01$ and 0.17 , demonstrating that the hole mobility remains virtually unchanged in a surprisingly wide range of doping. We note that the magnitude of the hole mobility in LSCO (order of $10 \text{ cm}^2/\text{Vs}$ at 300 K) is almost the same as that in YBCO;⁸ this suggests that the hole mobility in the CuO_2 planes is essentially universal among the cuprates. Interestingly, typical metals (such as iron or lead) show similar values of carrier mobility, $(ne\rho)^{-1}$, at room temperature.⁸

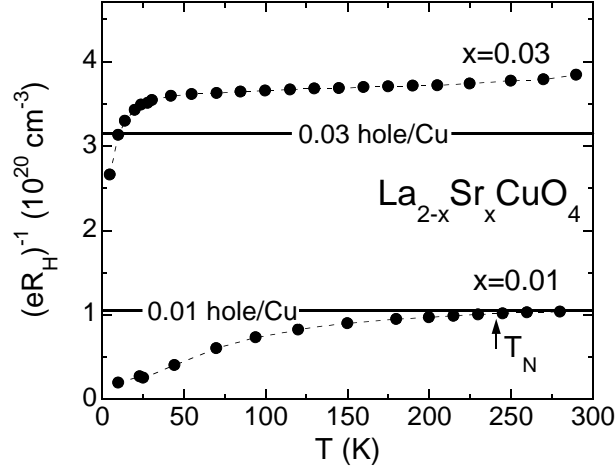


Figure 4. The apparent hole density of carriers $n = (eR_H)^{-1}$ for the two lightly-doped LSCO crystals; solid lines indicate the nominal value n_h .

The region that is characterized by the metallic transport behavior ($d\rho_{ab}/dT > 0$) is depicted in the phase diagram (Fig. 2); evidently, it extends widely in the phase diagram and essentially ignores the changes in the magnetic properties. It is worth noting that the normal-state resistivity in superconducting LSCO was studied^{9,10} by suppressing superconductivity with 60-T magnetic fields and an increase in ρ_{ab} at low temperature was observed up to optimum doping; thus, the high mobility of holes at moderate temperature and localization at low temperature appear to be essentially unchanged in the normal state in the whole underdoped region, all the way from $x = 0.01$ to 0.15.

Another evidence for unexpected metallic charge transport in the AF cuprates can be found in the Hall coefficient R_H . The apparent hole density $n = (eR_H)^{-1}$ obtained for the LSCO samples with $x = 0.01$ and 0.03 (Fig. 4) is essentially temperature independent in the temperature range where the metallic behavior of $\rho_{ab}(T)$ is observed, which is exactly the behavior that ordinary metals show. Moreover, n agrees well with the nominal hole concentration $n_h = 2x/V$ at $x = 0.01$, which means that all the doped holes are moving and contributing to the Hall effect even in the long-range-ordered AF state down to not-so-low temperatures until disorder causes the holes to localize. For higher doping, the ratio n/n_h exceeds unity and reaches a value of ~ 3 at optimum doping.

4. Discussions

4.1. *Unusual Metallic Transport*

It is useful to note that the absolute value of ρ_{ab} for $x = 0.01$ is as large as 19 m Ω cm at 300 K. If we calculate the $k_F l$ value (k_F is the Fermi wave number and l is the mean free path) using the formula $hc_0/\rho_{ab}e^2$ (c_0 is the interlayer distance), which implicitly assumes a *uniform* 2D electron system and the Luttinger's theorem, the $k_F l$ value for $x = 0.01$ would be only 0.1; this strongly violates the Mott-Ioffe-Regel limit for metallic transport, and thus the conventional wisdom says that the band-like metallic transport is impossible for $x = 0.01$. In other words, the metallic transport in the slightly hole-doped LSCO is a strong manifestation of the “bad metal” behavior.¹¹

Very recent angle-resolved photoemission spectroscopy (ARPES) measurements of lightly-doped LSCO crystals have found¹² that “Fermi arcs” develop at the zone-diagonal directions in the \mathbf{k} -space, on which metallic quasiparticles are observed. These Fermi arcs are different from the small Hall pockets and apparently violate the Luttinger's theorem, because the Fermi surface is partially destroyed and thus the enclosed *area* is not well-defined. Therefore, at least phenomenologically, such violation of the Luttinger's theorem by the Fermi arcs allows the system to have a small effective carrier number and a “large” k_F value at the same time, which enables the metallic transport to be realized in the lightly hole-doped regime. (Thus, the $k_F l$ value estimated under the assumption of a uniform 2D system is obviously erroneous.)

4.2. *Difficulty of Metallic Transport in the Antiferromagnetic State*

How can such an unusual metallic transport and the relatively high mobility of doped holes be possible in the long-range-ordered AF phase? It has been known for a long time that a single hole doped into a two-dimensional square antiferromagnet should have a very low mobility because of the large magnetic energy cost of the spin bonds broken by the hole motion, although quantum effects allow the hole to propagate.^{13,14} Despite this common knowledge, our resistivity and the Hall coefficient data demonstrate that the doped holes in the AF state can have the mobility nearly as high as that at optimum doping, which means that the holes manage to move without paying the penalty for frustrating AF bonds. This striking contradiction is not restricted to the simple one-band model implicitly hypothesized in the above argument. Whatever the transport mechanism is, the doped

holes should have an extremely strong coupling to the AF background; otherwise such a small amount of holes as 2% would not be able to destroy the AF state.¹ At the same time, this strong coupling tends to localize the holes arbitrarily distributed in the AF background, since the spin distortion created by a hole in the rigid Néel state destroys the translational symmetry. Therefore, the unusually metallic charge transport in the AF phase requires a novel mechanism to be realized in the lightly-doped cuprates.

4.3. Role of Stripes

To the best of our knowledge, the only possibility for the metal-like conductivity to survive under the strong coupling of holes with the magnetic order is when the holes and spins form a superstructure which restores the translational symmetry. A well-known example is the striped structure,^{14,15,16} where the energy cost for the distortion of the spin lattice is paid upon the stripe formation and then the holes can propagate along the stripes without losing their kinetic energy. In fact, the striped structure has been already established¹⁷ for $\text{La}_{2-x-y}\text{Nd}_y\text{Sr}_x\text{CuO}_4$, and there is now growing evidence for the existence of stripes in other hole-doped cuprates,^{3,18,19,20,21} the case being particularly strong for LSCO and YBCO in the lightly-doped region. Moreover, the mesoscopic phase segregation into the metallic paths (charge stripes) and the insulating domains (AF regions) offers a natural explanation about why the apparent $k_F l$ value can be so small in the regime where metallic transport is observed.⁸ Existence of such charged magnetic-domain boundaries are actually indicated by our recent in-plane anisotropy measurements of the magnetic susceptibility of lightly-doped LSCO.²²

One might wonder about the nature of the Hall effect when the conductivity occurs through the quasi-one-dimensional (1D) stripes. Indeed, it was shown that the Hall effect tends to disappear in $\text{La}_{1.4-x}\text{Nd}_{0.6}\text{Sr}_x\text{CuO}_4$ (LNSCO) upon the transition into the static stripe phase.²³ Against our intuition, however, the quasi-1D motion itself does *not* necessarily drive the Hall coefficient to zero. The quasi-1D confinement dramatically suppresses the transverse (Hall) *current* induced by the magnetic field, but the same large transverse resistivity restores the finite Hall *voltage*, because $R_H \sim \sigma_{xy}/\sigma_{yy}\sigma_{xx}$. For the same reason, for instance, the well-known charge confinement in the CuO_2 planes in cuprates does not prevent generation of the Hall voltage along the c -axis ($H \parallel ab$).²⁴ Therefore, the Hall-effect anomaly in LNSCO must be caused by some more elaborate mechanism rather than simply due to the quasi-1D nature of the transport. One possibility is that the anomaly in LNSCO is due to the peculiar arrangement of stripes which alter their direction from one CuO_2 plane to

another and thereby keeping σ_{yy} from vanishing; on the other hand, the unidirectional stripes²⁵ in pure LSCO would naturally keep the Hall coefficient unchanged, and thus the apparently contrasting behavior of the Hall effect in lightly-doped LSCO and LNSCO can be compatible with the existence of the stripes in both systems. Another possible source of difference between the two systems is the particle-hole symmetry inside the stripes: It has been proposed that the vanishing Hall coefficient in LNSCO is essentially due to the particle-hole symmetry realized by the 1/4-filled nature of the stripes near the 1/8 doping;^{26,27} if, on the other hand, the stripes at small x values are not exactly 1/4 filled, it is natural to observe non-vanishing Hall coefficient in LSCO, in the context of these theories.^{26,27} Also, it is possible that the finite Hall resistivity in LSCO is caused the transverse sliding of the stripe as a whole; in fact, very recent optical conductivity measurements of lightly-doped LSCO have concluded that the sliding degrees of freedom are important for the realization of the metallic transport in this system.²⁸

From the above discussion, it is clear that the metallic in-plane charge transport we observe in the AF state is most likely governed by the charge stripes. Given the fact that the hole mobility at moderate temperatures is surprisingly insensitive to the hole doping all the way up to optimum doping, it is tempting to conclude that the charge transport in cuprates that show the maximal T_c is also governed by the stripes. Recent STM studies of optimally-doped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ compounds, where periodic spacial modulations of the local density of state are observed,^{29,30} also seem to support this conclusion. The implication of such a conclusion on our understanding of the high- T_c superconductivity is rather significant. Since the ordered static stripes are known to *kill* superconductivity, it must be the fluctuating nature of the stripes that facilitate the superconductivity at such high temperatures. There are already some theoretical proposals to explain the high- T_c superconductivity on the basis of the fluctuating stripes^{14,31,32} or charge fluctuations.³³ The system we are dealing with may indeed be the “electronic liquid crystals”,¹⁵ which are quantum-fluctuating charge stripe states; our recent studies of the in-plane resistivity anisotropy of lightly-doped cuprates have found²¹ that the resistivity is smaller along the stripe direction but the magnitude of the anisotropy is strongly dependent on temperature, which suggests a crossover between different electronic liquid crystal phases occurring in the cuprates, and the low-temperature phase appears to be an electron nematics.³⁴ Clearly, more experiments are needed to fully understand such a new state of matter, and to finally elucidate the mechanism of the high- T_c superconductivity.

5. Summary

It is shown that the doped holes in cuprates are surprisingly mobile in the long-range-ordered antiferromagnetic state at moderate temperatures, which is evidenced both by the metallic $\rho_{ab}(T)$ behavior and by the almost temperature-independent $R_H(T)$. It is emphasized that the *mobility* of the doped holes at moderate temperatures is virtually unchanged from the lightly hole-doped antiferromagnetic compositions (where the dominance of the stripes is very likely) to the optimally-doped superconducting composition, which implies that the charge transport even at optimum doping is essentially governed by the stripes.

Acknowledgments

This work was done in collaboration with A. N. Lavrov, S. Komiya, X. F. Sun, and K. Segawa. Stimulating discussions with S. A. Kivelson are greatly acknowledged. We also thank D. N. Basov, A. Fujimori, and J. M. Tranquada for collaborations and helpful discussions.

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